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A COMPARISON OF THE V/STOL HANDLING QUALITIES OF THE VAK-191B WITH THE REQUIREMENTS OF AGARD REPORT 577 AND MIL-F-83300

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SUMMARY

The handling qualities of the VAK-191B VTOL aircraft are compared with current V/STOL handling-qualities requirements. Generally, the aircraft's handling qualities were superior to other V/STOL fighter-type aircraft; however, several deficiencies would seriously affect shipboard V/STOL operation. These include poor hovering precision, inadequate mechanical control characteristics, nonlinear pitch and roll response, an uncommanded movement of the height (thrust) control lever, low-pitch control sensitivity, excessive dihedral effect, and inadequate overall thrust response. The attitude-command control system resulted in reduced pilot workload during hover and low-speed flight.

The study disclosed gaps in the current handling-qualities requirements, particularly for operation aboard ships. AGARD Report 577 provides more comprehensive coverage than does MIL-F-83300 in the area dealing with STOL operation.

INTRODUCTION

The possibility of using a V/STOL aircraft to meet the operational requirements of aviation and non-aviation ships and for other mission deployments has been studied by the U.S. Navy with increased interest in recent years. Because of the desirability to operate V/STOL aircraft from limited areas on small ships and under adverse environmental conditions, severe requirements are imposed on stability and control and handling qualities. Poor handling qualities increase pilot workload and can severely compromise mission effectiveness. Moreover, definitive handling-qualities requirements are needed to aid the design of future V/STOL aircraft.

Specifications for V/STOL handling qualities have been developed from a background of flight experience using a wide variety of V/STOL concepts. Two documents that are currently available to aid in the design of V/STOL aircraft are AGARD Report 577 (ref. 1) specification and MIL-F-83300 (ref. 2). Neither of these documents has been operationally validated and many design requirements for shipboard operation are not covered.

In order to help define design requirements for future V/STOL fighter aircraft, the U.S. Navy, in a cooperative program with the Federal Republic of Germany (FRG), conducted a flight-test program on the VAK-191B VTOL fighter aircraft. This aircraft, shown in figure 1 and described in reference 3, uses the lift plus lift-cruise VTOL concept and is equipped with a triply redundant, electrohydraulic, 100-percent authority, fly-by-wire (FBW) control system. As such, it represented

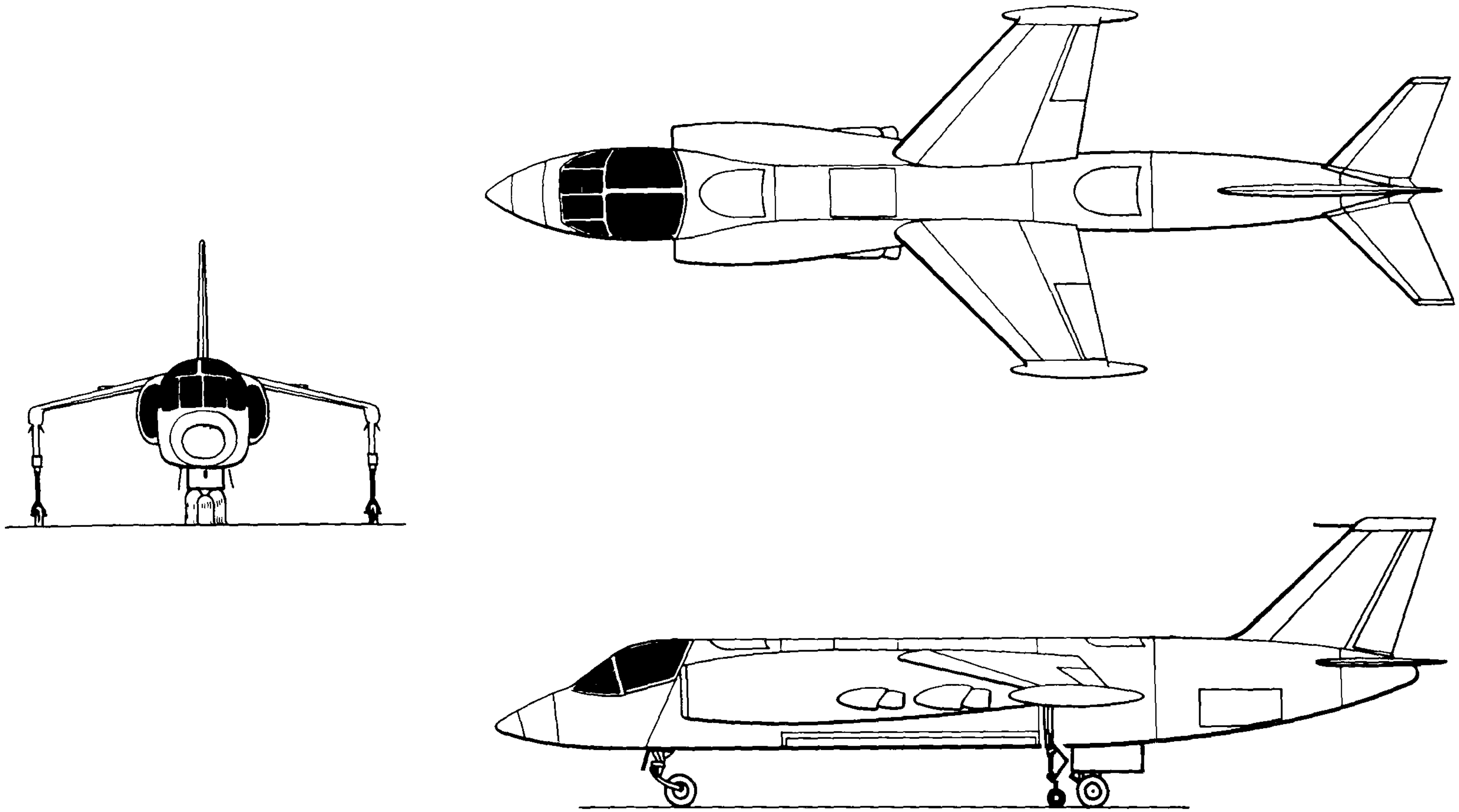


Figure 1.– VAK–191B test aircraft.

an advanced state-of-the-art "operational-type" VTOL aircraft from which design requirements for future VTOL aircraft could be obtained. Of particular interest was an evaluation of the aircraft's handling qualities to determine how well it meets existing V/STOL handling-qualities requirements.

The purpose of this report is to:

1. Clarify V/STOL handling-qualities requirements with emphasis on shipboard operations for fighter aircraft.

2. Determine how well the handling qualities of the VAK-191B aircraft comply with existing handling-qualities specifications.

3. Identify omissions in the current handling-qualities specifications.

The report also compares the measured handling qualities of the VAK-191B aircraft with the requirements of AGARD Report 577 and specification MIL-F-83300; pilot comments of the capabilities and limitations of the VAK-191B are included. The flight-test program was limited by the experimental nature of some of the aircraft equipment; consequently, not all the handling qualities listed in the aforementioned references could be evaluated. From the information that was available, however, an attempt is made to judge the results in terms of the requirements for a Navy VTOL fighter mission.

RESULTS AND DISCUSSION

The various items in the V/STOL handling-qualities specifications are discussed below in the order outlined in AGARD Report 577 because the AGARD document was used by the US/FRG flight-test team as a guideline in conducting the flight-test program on the VAK-191B.

Tables 1 through 16 list handling-qualities specifications from references 1 and 2, corresponding values determined from tests of the VAK-191B, and pilot comments regarding handling characteristics of the VAK-191B. Most pilot comments were taken from reference 4.

Characteristics of Control Systems

Control breakout forces– The breakout forces, including friction and preload shown in table 1, indicate that the VAK-191B values fall within the range of values listed in the AGARD report (except for yaw), but are higher than those recommended for level 1 operation in MIL-F-83300. Pilots' comments indicate a preference for lower forces for pitch and roll to achieve the desired precision of control when using an attitude-command control system, particularly when hovering in ground effect (IGE). Relatively high yaw forces, when combined with the sluggish aircraft response in yaw, made sideslip control more difficult at low speeds.

Control force gradients (table 2)– Except for the yaw axis, the force gradients used on the VAK-191B are within the ranges specified. Even so, the control characteristics were not entirely satisfactory. For example, the pitch-force gradient was less than the maximum allowable. However, the pilot desired an even lower gradient because, with the attitude command type of control system used, it is necessary to continuously hold the stick forces to maintain pitch attitude to achieve a translational velocity. This could result in less precise positioning, particularly for more demanding tasks such as shipboard operation. In addition, although the control-force gradient was linear, aircraft pitch response was nonlinear. This is due to the manner in which the pitch moments are produced. (See figure 2 for schematic of flight-control system.) For the first 2 in. of stick travel, engine bleed air provides the pitch moments, after which lift-engine (LE) thrust modulation is added. As discussed more fully in the section on pitch control, nonlinear aircraft response increases pilot workload and results in less accurate positioning.

In roll, the breakout force and the force gradient relationship was considered unsatisfactory and did not meet AGARD-577 criteria. This is because the force required for 1-in. (2.54 cm) travel from trim is less than the breakout force. This results in poor control feel about trim. In STOL operation, the force gradient in roll was considered too large because the attitude-command control system required that the lateral forces be maintained while in turning flight. Reduced forces would improve precision of alignment in approach.

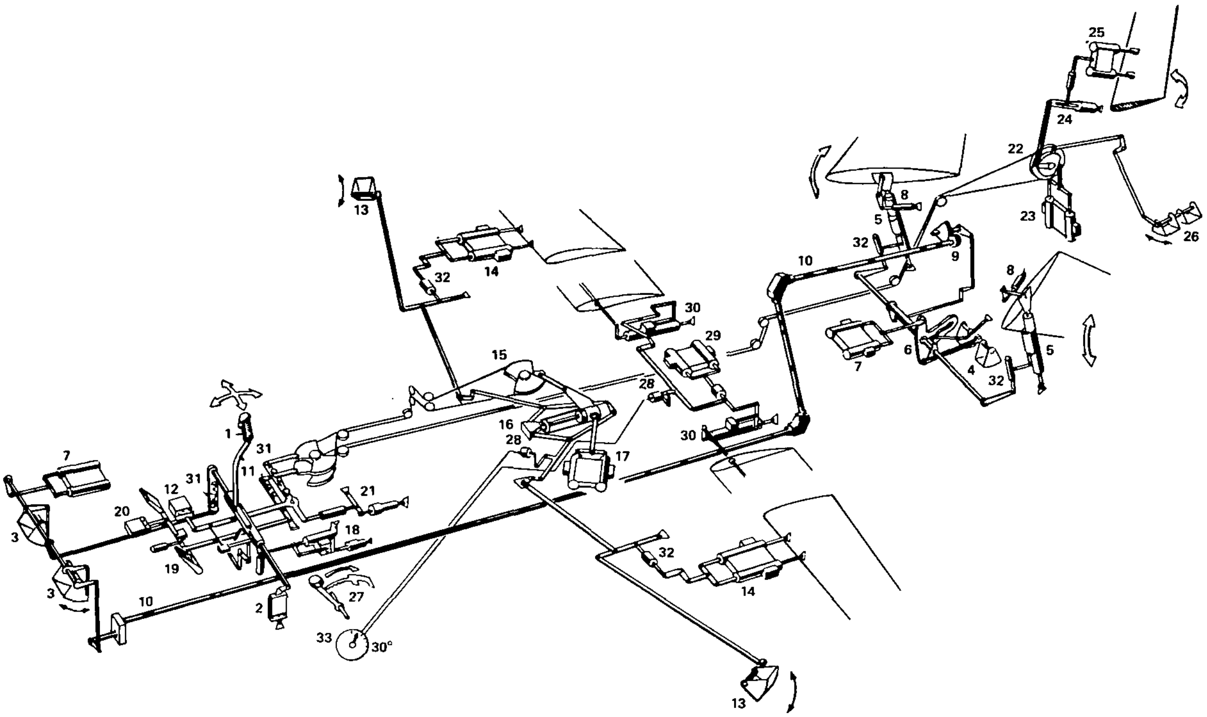
In yaw, the gradient was larger than allowed by both handling-qualities specifications. Because the breakout force is high, the gradient must also be high (greater than the breakout force) to avoid control centering problems. The VAK-191B could be improved in this regard by reducing the breakout force, which, in turn, would allow a reduced force gradient, thereby improving heading control accuracy and control of sideslip.

Control force harmony ratio (table 2)– Control force harmony (i.e., the ratio of maximum control force for one axis compared to another axis) for the VAK-191B falls within the guidelines given in the AGARD report (no values are given in MIL-F-83300). Proper harmony is more important for attitude command systems because the forces are held for longer periods of time. A more accurate definition of control force harmony than that given in the AGARD report is needed, to take into account the differences likely to occur where more sophisticated (higher order) control systems are used and when side-stick controllers or other unconventional control systems are used.

Height-control systems (table 3)– One of the more serious deficiencies of the VAK-191B was an uncommanded movement of the height-control lever (throttle) which could occur during certain hovering operations. This was due to the pitch attitude stabilization system having the authority to move the lift-engine throttle (height control) against the pilot's hand to reduce engine thrust to stay within prescribed temperature limits. This uncommanded movement occurred on several occasions, while hovering in ground effect (IGE), when recirculation of the engine exhaust resulted in inlet temperature increases with resultant thrust changes. Another height-control system deficiency was the lack of an adjustable friction device. This is needed to prevent unintentional height loss resulting from movement of the control when the pilot removes his hand to adjust other controls.

AGARD Report 577 requires that the height control remain fixed at all times unless moved by the pilot or some automatic system. A variable-friction adjustment is also required since less friction is desired for hover operations than for cruise. Specification MIL-F-83300 does not have specific requirements for height-control systems.

Powered-control systems (table 3)– Another mechanical control system deficiency noted was the poor lateral damping of the control stick. The low value of viscous damping contributed to a



1. COCKPIT CONTROL GRIP
2. POTENTIOMETER (LONGITUDINAL STICK)
3. FORWARD PITCH-CONTROL REACTION NOZZLE
4. REAR PITCH-REACTION NOZZLE
5. TAILPLANE-POWER ACTUATORS (HYDRAULIC)
6. INTERCONNECTING-CAM-LINKAGE OUTPUT
7. DUPLEX ACTUATOR, HYDRAULICALLY OPERATED, ELECTRICALLY SIGNALLED (PITCH AXIS)
8. TAILPLANE DAMPERS
9. REACTION-NOZZLE GEAR AND QUADRANT
10. FORWARD AND REAR NOZZLE INTERCONNECTING TORQUE SHAFT
11. CONTROL COLUMN
12. POTENTIOMETER (LATERAL STICK)
13. ROLL-CONTROL NOZZLE (LEFT AND RIGHT)
14. AILERON-CONTROL DUPLEX ACTUATOR, HYDRAULICALLY OPERATED, ELECTRICALLY SIGNALLED
15. CABLE DRIVE TO TENSIONER UNIT
16. CONTROL INPUTS, MECHANICAL INTEGRATION UNIT
17. DUPLEX SERVO ACTUATOR, ELECTRICALLY SIGNALLED
18. ARTIFICIAL-FEEL UNITS AND TRIM SERVOS
19. RUDDER PEDALS
20. POTENTIOMETER (RUDDER PEDALS)
21. FEEL UNIT
22. CABLE DRIVE TO RUDDER QUADRANT (INPUT)
23. DUPLEX SERVO, HYDRAULICALLY OPERATED, ELECTRICALLY SIGNALLED (YAW AXIS)
24. RUDDER-LIMITER CONTROL
25. DUPLEX RUDDER POWER ACTUATOR
26. YAW-CONTROL REACTION NOZZLES
27. FLAP LEVER
28. TRANSDUCER
29. DUPLEX SERVO ACTUATOR, HYDRAULIC
30. FLAP ACTUATOR (BOTH SIDES), HYDRAULIC
31. HYDRAULIC COUPLING
32. SPRING LINK
33. AILERON- AND FLAP-POSITION INDICATOR

Figure 2.– Schematic of the flight-control system of the VAK–191B.

lateral pilot-induced oscillation (PIO). This was considered unsatisfactory; both handling-qualities references require that oscillations of powered-control systems be well damped.

Another control problem could occur following a powered-control system failure. The VAK-191B mechanical backup system was judged to be unsatisfactory for hover because of excessive backlash and large friction breakout and force gradients. Based on piloted simulator studies and tests on a pedestal test rig, failure of the power-control system would not allow a safe landing because of these poor mechanical characteristics. The need to provide satisfactory control characteristics following a failure of the powered-control system is noted only in the AGARD report.

Trim systems– There is an obvious need to provide trim systems that operate fast enough to keep control forces small during changes in aircraft configuration or speed and during any maneuver consistent with service use. The need to maintain low control forces by adequate trim facilities would be more important for shipboard operation where greater precision of flight path and touchdown is required. As noted in table 4, both handling-qualities references have requirements in this regard. Pilots' comments indicate that the pitch trim rate on the VAK-191B would be too slow for the forward and sideward positionings required in approaches to a moving shipboard landing area. As previously noted, the need to trim out control forces is more important with attitude-command systems where forces must be maintained for longer periods of time to hold a given aircraft attitude.

Additional concern was expressed over the inability to prevent "runway" trim with the system used on the VAK-191B aircraft. Also, in the event of a stability augmentation system (SAS) failure, it was not possible to provide trim capability.

Thrust-vector controls– Thrust-vector control characteristics should allow accurate control of flight path and airspeed as desired during transition as well as accurate ground positioning in hover. A selected setting should be held indefinitely to avoid unintentional drift and cross-trimming. The system used on the VAK-191B provided rapid thrust-vector movement, but the tendency of the nozzles to drift slightly from their selected setting could affect hovering precision.

The requirement that the pilot's hand be removed from the throttle when making thrust-vector nozzle adjustments was considered to be undesirable when operating close to obstacles. As a result, the pilot preferred not to use nozzle adjustment for fore-and-aft positioning. This point is covered in greater detail in Sec. 1.8 of AGARD Report 577. No requirement is listed for this item in MIL-F-83300.

Generally, the mechanical control characteristics of the VAK-191B were considered to be unsatisfactory by the pilots. This opinion was substantiated by the fact that the system did not meet many of the requirements stated in the two handling-qualities references. Although there were no major differences in the control-system specifications between the two handling-qualities references, AGARD Report 577 covered a broader scope of items peculiar to V/STOL control systems. A better design guide is needed on the mechanical control characteristics for advanced V/STOL control systems.

Longitudinal Stability and Control

Pitch-control power— The total amount of pitch-control power required for V/STOL operation depends essentially on three inputs: (1) how rapidly the aircraft must be *maneuvered,* (2) the magnitude of *trim* changes associated with power, flaps, or thrust-vector-angle changes, and (3) pitch-angle changes required to correct for *upsets* due to gusts, recirculation, or other disturbances.

As shown in table 5, the total available power for pitch-angular acceleration (1.0 rad/sec^2) on the VAK-191B was larger than that required by the handling-qualities references and was considered adequate for hover out of ground effect. Pitch-attitude control of the VAK-191B deteriorated when close to the ground, however, because recirculation of engine exhaust reduced the maximum differential thrust available for pitch moments. Even relatively large amounts of control power may not be completely satisfactory for landing on a moving deck if pitch angular acceleration is the sole means of obtaining fore and aft positioning. Studies (ref. 5) of landing on a small platform under poor conditions (turbulence and heavy seas) indicate that a velocity command-control system was needed for a satisfactory pilot workload. A blending of pitch attitude for inner-loop control with velocity-command outer-loop control will undoubtedly be more desirable when operating with a pitching, moving deck.

Control-power requirements are specified differently in the two V/STOL handling-qualities references. In AGARD Report 577, requirements are listed in two ways: (1) in terms of the individual requirements for maneuvering, trim, and upset, and (2) as a range of values typical of those required for a wide variety of V/STOL aircraft, including trim, upset and an allowance for how rapidly the aircraft is intended to be maneuvered. By considering each individual control-power need and the type of control system, the AGARD criteria are useful as a design guide and establish a more realistic total control power for a specific aircraft configuration. Specification MIL-F-83300 presents the requirement in terms of a pitch attitude change after 1 sec, as measured in flight tests, with the wind from the most critical direction. Neither of the handling-qualities guides specify translational control power values or means for relaxing angular acceleration capabilities in the event that velocity command-control systems are used. Clearly, there is a strong need to improve pitch-control power requirements to account for the use of more advanced control systems and to reflect the more demanding needs for shipboard operation.

Pitch-control sensitivity— Control sensitivity has a major influence on the pilot's impression of aircraft response and precision of control. With conventional control systems, pilots prefer to use small, abrupt, high-frequency, control inputs to adjust aircraft attitude to obtain a desired translation over the ground. If control sensitivity is too low, it creates the impression of sluggish response; consequently, the pilot compensates by making large, gross control motions that result in pilot fatigue and reduced accuracy of aircraft positioning. The VAK-191B pitch-control sensitivity was 1.25° pitch-angle change in 1 sec for the first inch (2.54 cm) of stick movement. Both handling-qualities specifications require at least a 3° change in 1 sec per inch (2.54 cm) of stick deflection. This low pitch-control sensitivity of the VAK-191B was judged inadequate because aircraft response was too sluggish for small control inputs. A further deterioration in precision of pitch-attitude control due to nonlinear response was apparent when larger control deflections were used. This aspect is discussed in the next section.

Linearity of aircraft response– Constant (linear) control effectiveness is desirable for two reasons: (1) the pilot may use control position to indicate margins available for trim and maneuvering, and (2) overcontrolling tendencies can occur when nonlinear characteristics are present because of the pilot's inability to predict the final aircraft response. AGARD Report 577 specifies that an aircraft's response to control input should be constant or, if not constant, should not abruptly increase or change sign. Specification MIL-F-83300 is more general, stating that no objectional nonlinearities should exist.

The VAK-191B response to pitch-control inputs became nonlinear at approximately 5.08 cm (2 in.) of stick movement from neutral, due to the use of a combined bleed-air/thrust-modulation control concept. When small pitch-control inputs in the differential thrust control deadband were made, an oscillatory aircraft motion of about 0.5 Hz and 2° pitch amplitude resulted, which made precision hover more difficult.

Longitudinal-control characteristics in takeoff (table 6)– Rolling vertical takeoff (RVTO) and short takeoff (STO) are desirable operational modes, particularly for jet-lift aircraft, to help reduce ground erosion, hot-gas ingestion, recirculation, and aerodynamic suckdown, as well as to improve payload capability by taking advantage of aerodynamic lift. Both handling-qualities documents specify that the effectiveness of the pitch control shall not restrict takeoff performance, and shall be sufficient to prevent overrotation to undesired attitudes.

For several reasons, the VAK-191B aircraft pitch attitude was difficult to control accurately in takeoff runs. First, the large ground reaction moment associated with the bicycle landing gear geometry made it difficult to prevent pitch overshoots at liftoff in spite of the pilot's anticipation of this change in pitch response. This pitch-up tendency was considered undesirable and limited the potential benefits of using aerodynamic lift for improved takeoff performance. A second factor that reduced pitch-attitude control effectiveness in takeoff was a mechanical feedback problem in the lift-engine throttle lever. Due to the manner in which the high authority stability and augmentation system functioned, the throttle lever could push back the pilot's hand if a reduction in thrust was required. This feedback occurred more frequently with smaller T/W values, with increased airspeed, and when the pilot introduced a commanded-pitch input at liftoff. This uncontrolled-for movement of the lift-engine throttle lever was considered highly undesirable because it increased height-control coupling problems. There are no handling-qualities requirements in either reference that bear directly on this adverse-control-system feature.

The piloting takeoff procedure for RTO and STO should not be complicated to the extent that height control (as affecting liftoff performance) is compromised. The complicated procedures that were required during takeoff for the VAK-191B illustrate the problem. Because of the need to start the lift engines during the takeoff roll (to avoid jet efflux erosion of the runway surface), many accurately timed pilot inputs were required (15 distinct steps) during the takeoff run. In addition, it was not possible to check for proper pitch-control functioning until after the aircraft had started its takeoff run. This increased pilot workload to the saturation point and compromised the accuracy of takeoff performance. This operational concern for downwash effects could be equally serious for shipboard operation. The need to guard against complicated takeoff procedures and provisions for checking proper control functioning are covered adequately in the handling-qualities references.

Longitudinal-control characteristics in landing– The requirement for pitch-control effectiveness can become critical in short landings because of possible lift losses and adverse trim changes as the aircraft enters ground effect. As noted in table 7, both handling-qualities documents specify the need to provide adequate control power to adjust pitch attitude as necessary close to the ground. In terms of total control power, the VAK-191B was satisfactory, since only a mild nose-up trim change occurred in entering ground effect. However, the lift-engine thrust modulation feedback previously discussed for takeoff could cause landing (touchdown) problems if very low touchdown speeds were used. For example, if a commanded attitude above approximately 5° nose-up was held or imposed at touchdown, the stabilization system could produce a throttle increase rapid enough to snatch the throttle lever from the pilot's hand. Again this condition is not covered in either of the handling-qualities references.

Lateral-Directional Stability and Control

Roll-control power– As discussed previously for pitch-control power, the total amount of roll-control power required depends on proper summation of the individual requirements for maneuvering, trim, and upset. As shown in table 8, the roll-control power available on the VAK-191B for bank-angle control meets the criteria of both handling-qualities references and was judged to be adequate for hover in no wind. In forward flight at low speeds, however,the bank-angle limit of ±15° for full-stick throw (maximum provided with the attitude-command system) was judged to be too small at speeds of about 60 knots, and would not allow a quick enough alignment from a nominal centerline offset.. Although AGARD Report 577 provides for different values of control power, depending on the type of control system employed, a maximum value of bank angle for STOL maneuvering should be included. In addition, as discussed later under "dihedral effect," the VAK-191B did not have sufficient roll-control power for crosswind operation.

Satisfactory control of both lateral translation and bank angle would be particularly important for shipboard operation where alignment with a moving and canted deck can impose more severe roll-control requirements.

As discussed in the section on pitch-control power, there is evidence from piloted simulator studies (ref. 5) that direct translational control can greatly improve precision of control in approach and touchdown for shipboard operation onto a small platform in heavy seas. Translational control criteria for lateral positioning are included only in AGARD Report 577 wherein a lateral acceleration range of values between 0.08 to 0.12 g in wings-level sideward flight is specified. Although the use of translational control greatly reduces the amount of angular acceleration control power required, some residual roll angular acceleration capability will be needed for wing alignment at touchdown. Further clarification is needed on the tradeoffs between translational and angular control methods, including proper phasing out of translational control with increased forward speed.

Roll-control sensitivity– The optimum value of roll-control sensitivity depends, to a large extent, on the vehicle dynamics. Generally, the pilot prefers quick response without overshoot or PIO tendencies. Specification MIL-F-83300 allows for a relatively large spread in sensitivities 0.03–0.14 rad/cm (4°–20°/in.). AGARD Report 577 is more restrictive, specifying different ranges of values, depending on the type of control system used and the mode of operation.

Although the roll-control sensitivity of the VAK-191B falls within the bands presented by both handling-qualities specifications (see table 8), the system was not completely satisfactory. First, when brisk maneuvering was attempted, a lateral PIO was encountered; and, second, the SAS introduced a nonlinear restoring moment in roll reversals. The reasons why the PIO tendencies were encountered with the attitude-command control system on the VAK-191B are not completely clear; however, as noted previously in the discussion on control systems, a contributing factor could be the poor mechanical damping characteristics of the control stick in lateral movements.

Linearity of aircraft response– As noted previously for pitch control, linearity of aircraft response to control input is desired by the pilot. This is true to a greater extent for the roll axis because of the need to control bank angle more accurately, particularly for shipboard operation. In addition, with conventional control systems, the pilot tends to use cockpit control position as an indication of control margins needed to provide for trim changes and upsets or disturbances.

Although the VAK-191B roll-control system provided linear aircraft response with control deflection when the control was initially moved from the trim position, the response was nonlinear when the cockpit control was returned to neutral position (see comments in table 8 and schematic of control system (fig. 2)). This was due to peculiarities of the SAS. When the cockpit control was returned to center after an input of over 60-percent deflection, the roll servo reversed sign, introducing a large roll overshoot that could not be precisely anticipated by the pilot. Neither of the handling-qualities specifications treat this type of nonlinear control system behavior adequately.

Cross-coupling (sideslip excursions)– Roll-control inputs for maneuvering at STOL operating speeds can cause large changes in heading (sideslip), pitch attitude, and vertical lift for most V/STOL configurations. Of these, the sideslip excursions have proved to be the most important, and the need to limit sideslip excursions has been included in handling-qualities specifications from the start.

The lateral-directional cross-coupling characteristics of the VAK-191B were evaluated in a speed range from 0 to 120 knots, with primary emphasis at a 60-knot approach speed (table 9). Although the adverse yaw was very small at 60 knots, coordinated turns were relatively difficult to execute because of the inability to precisely control sideslip near zero by use of the rudder. Aileron-only turns were preferred to minimize sideslip excursions. Because of the large dihedral effect (discussed next), sideslip excursions required relatively large lateral trim requirements that could saturate the lateral control system.

Both handling-qualities references state limits for turn coordination in terms of $\Delta\beta/\Delta\phi$, with a much larger allowable value stated in MIL-F-83300. The allowable values of sideslip excursion need improved definition, specifically for the instrument approach task and to reflect how other related factors, such as heading lag in turn entries, roll damping, and dihedral effect influence pilot rating.

Dihedral effect– Although positive dihedral effect is desired by the pilot, the absolute amount tolerable depends on many factors, including the aircraft's dynamics, turn coordination characteristics, roll-control power, and spiral stability. Because many VTOL aircraft inherently have too much positive dihedral effect at low speeds, it has been necessary to restrict the amount allowed so that sufficient excess roll-control power is available for maneuvering and operation in turbulence and crosswinds. As shown in table 9, both handling-qualities references recognize the need to limit positive dihedral effect. Specification MIL-F-83300 states that a margin of 50-percent roll-control power should be available to the pilot.

The VAK-191B experienced a strong positive dihedral effect that limited crosswind operation and lateral sideslip maneuvers to undesirably low values (approximately 10° sideslip at 50-knot forward speed). Because the roll-restoring moment is caused by a combination of factors – including lift-engine momentum drag and aerodynamic and power-induced flow characteristics over the wing – the amount of sideslip available to the pilot before roll-control saturation occurs depends on engine power, angle of attack, and airspeed. The lack of a completely satisfactory system to warn the pilot of control saturation was another concern. In a skidding turn, for example, the attitude command-control laws automatically provide roll control to compensate for asymmetric moments with the control stick centered. The pilot thus loses a natural warning of limited trim capability degrading pilot rating, even though the servo control position was presented on a head-down display. This nonlinear response (maneuvering deadband) can quickly lead to a dangerous situation if roll upsets are encountered at low altitude.

A control margin to guard against upset is difficult to establish from the data base available. The 50-percent margin noted in MIL-F-83300 is arbitrary and may unduly penalize some VTOL designs that are not required to be maneuvered extensively. Improved criteria are needed, taking into account multicontrol inputs and wind-direction considerations.

Yaw-control power and sensitivity– For most VTOL aircraft in hover, experience has indicated that relatively smaller amounts of control power are needed for the yaw axis than for the pitch and roll axes. Although the total value must include requirements for trim and upset,the major demand has been for maneuvering. The directional characteristics of the VAK-191B at speeds below 20 knots were typical of other jet VTOL concepts in that no directional stability was evident, and yaw response was sluggish (see table 10). In hover, the aircraft tended to drift slowly out of wind, indicating small directional instability. At about 30 knots, positive directional stability was evident. The values shown in table 10, when compared to the handling-qualities requirements, confirm that both control power and sensitivity are too low at hover. As forward speed was increased, rudder effectiveness increased, and the aircraft became too sensitive for precise directional control. This nonlinear response was due to the fact that the gain for the yaw-rate command system remained constant regardless of forward speed. Because of this high yaw sensitivity even at low forward speeds (60 knots), the pilot preferred not to use rudder in turn entries. Large yaw/roll cross-coupling occurred during full-rudder-pedal-input turns because of the "aft only" location of the yaw reaction nozzles. On one occasion, the large rolling moment associated with lateral velocity during a large heading change maneuver saturated the lateral control system with no warning to the pilot.

Hover and Vertical Flight-Path Characteristics

Ground effect– During operations near the ground, most jet-type VTOL aircraft have experienced some form of unsteady dynamic behavior resulting from recirculation and impingement of engine exhaust gases on the undersurface of the aircraft. Depending in part on the type of control system used, precision of height control can be seriously degraded in landing and takeoff. The acceptable magnitude of disturbance will vary with both the mission and task.

The AGARD report criteria for ground-effect characteristics (noted in table 11) state the need to provide satisfactory aircraft behavior in ground effect for any wind condition, including a safe landing capability in the event of a power-control system or SAS failure. No parallel requirement is contained in MIL-F-83300.

The VAK-191B experienced random unsteadiness about all axes when hovering in no wind at heights less than about 7 ft (2.12 m). Because of the attitude stabilization system used, pilot control inputs required to maintain position were minimum. Positive (favorable) ground effect was evident during level attitude, no-wind conditions, creating minor pilot complaint due to nonlinear height-control response. Prolonged hover with a nose-up attitude, as might be required in a tail wind or in crosswinds, had to be avoided because of engine exhaust reingestion in the cruise engine inlet and rear lift-engine inlet, resulting in uncontrolled-for pitch attitude changes and loss of precision in height control. In addition, loss of the power-control system or SAS, particularly in the roll axis, would make a safe landing questionable. The reason for this, based on piloted simulator studies and tests on a static test-stand pedestal, is that reversion to the manual-control system increases the friction (breakout) forces to high values that would adversely affect precision of attitude control.

Ground-effect characteristics can be expected to be of greater concern for platform operation from small ships when only part of the aircraft is over the landing platform. More operational experience is needed to define handling-qualities criteria for these conditions.

Hovering precision– Hovering precision is necessary to ensure that a VTOL aircraft can operate in a confined space. The requirement for precise hover control will vary, depending on the type of aircraft, mission, and task.

AGARD Report 577 defines hovering precision in terms of the overall geometric dimension of the aircraft, allowing more leniency for operation out of ground effect (table 12). No requirement of this type is included in MIL-F-83300.

The VAK-191B exhibited satisfactory hovering precision when hovering in no wind in a level attitude by virtue of the benefits of the attitude-command control system. As previously noted, however, hovering with a nose-up attitude or in tail winds resulted in loss of pitch or height control, or both, due to nonlinear thrust response associated with hot-gas ingestion. In addition, precision of height control varied with the margin in T/W available, due to a nonlinear thrust requirement associated with an apparent positive ground effect, recirculation (ingestion) in the rear lift engine, and different thrust response-time constants between the front and rear lift engines. Pilot workload was relatively high because of the aforementioned items, and precision VTO characteristics would be considered inadequate for shipboard operations at low T/W values.

Vertical-thrust margins– Adequate vertical-thrust margins are needed for satisfactory height control to establish safe climbout procedures and to adjust sink rate as needed for touchdown.

As noted in table 13, both handling-qualities documents require a minimum T/W value of the order of 1.05 for takeoff. Vertical-thrust margin requirements in AGARD Report 577 criteria are more definitive, taking into account vertical-height damping. Vertical (height) damping levels affect the vertical-thrust margins needed, particularly if the height-damping characteristics are nonlinear with respect to height from touchdown. For landing, larger values of T/W (up to 1.1) are specified as vertical-height damping decreases to lower values. For shipboard operations, it seems reasonable to expect that generally higher T/W values (of the order of at least 1.1) may be needed to cope with the added problem of a heaving ship deck. Additional information is needed to more realistically specify vertical thrust margins, taking into account ship motion characteristics, simultaneous control usage, and environmental (wind shear) effects.

Height control for the VAK-191B was obtained by using the combined thrust variations of lift and the lift/cruise engine or by using a split-throttle arrangement to provide more gross thrust changes. Height control with matched throttles was considered satisfactory when a T/W of 1.1 was available and inadequate when T/W was at 1.05. With split throttles, height control was not satisfactory even with T/W on the order of 1.1, because of speed/attitude coupling problems associated with low throttle sensitivity, nonlinear height response due to recirculation, and ingestion of exhaust gases.

Height-control sensitivity and thrust response– Height (thrust) control sensitivity is a parameter that should be optimized to provide precise vertical flight-path maneuvering. A number of studies have indicated that a height-control sensitivity of the order of 0.12 g/cm (0.3 g/in.) of control movement is desired. A range of values is given in AGARD Report 577 (0.04–0.16 g/cm (0.1–0.4 g/in.)) to take into account the influence of vertical-height damping. No requirement is listed in MIL-F-83300.

The VAK-191B had inadequate thrust response with split-throttle (lift engines only) operation (0.016 g/cm (0.04 g/in.)). This low sensitivity resulted in excessive lags in height-control adjustments and was considered unsatisfactory. In addition, the front-lift engine had a faster thrust response than the rear engine; this caused problems in liftoff dynamics because of nonlinear pitch-attitude characteristics.

The thrust response of the lift engines was considered adequate; however, the lift/cruise engine response was inadequate, which led to overcontrolling tendencies. A particularly bad feature was the automatic limiting of maximum power, which created a region of throttle movement deadband. Neither of the handling-qualities specifications covers these nonlinear response characteristics adequately. It would appear desirable to provide a warning of an approaching deadband condition. In addition, protection for nonlinear response characteristics in multiengine aircraft should be provided.

Transition Characteristics

Transition handling characteristics can be more demanding for the lift plus lift/cruise concept because of the added pilot workload associated with lift-engine power management and the change in performance (power available for acceleration) due to the increase in lift-engine ram drag with increase in forward speed. The foregoing affect flight-path tracking precision, particularly for IFR operation.

Acceleration/deceleration– The need to have adequate control of longitudinal acceleration/deceleration is important for a number of reasons, including time at high specific fuel consumption, tactical considerations, and lift-engine life constraints. Each of the handling-qualities documents requires rapid and safe acceleration/deceleration capability for transition, without undue attention to loss of control or departure from a prescribed flight path (table 14).

For the VAK-191B, acceleration during transition from hover to conventional flight was executed by vectoring the lift/cruise engine nozzle at a rate that depended on the thrust margin available. Because of the lift-engine ram drag, longitudinal acceleration changed markedly over the conversion speed range. At the initial part of transition, the nozzles could be rotated more quickly, producing a longitudinal acceleration of about 0.5 g, or a positive climb gradient, or both. At the higher end of the speed range, climb rate had to be reduced to zero to allow acceleration to 200 knots, at which speed thrust was approximately equal to drag. Further acceleration could be achieved only after shutting down the lift engines (to reduce ram drag). This inability to accelerate to conventional flight in a climb profile would obviously be undesirable for a fighter mission. Conversely, however, decelerations from high speeds could be made quite rapidly. In the speed range up to 120 knots, the attitude-command response characteristics were satisfactory and greatly reduced pilot workload.

Flexibility of operation– The need to provide the pilot with the option of aborting the transition quickly is required in both handling-qualities documents (table 14). The VAK-191B met this requirement in principle, since the cruise-engine thrust vector could be adjusted as desired. But the available pitch-angle range of $\pm 15^\circ$ was considered inadequate due to lack of sufficient nose-up capability for steep climbs and quick stops. A value of 20° nose-up would seem to be sufficient.

AGARD Report 577 has a more stringent additional requirement for allowing a safe landing or wave-off in the event of a failure of a single engine with a multiengine aircraft or failure of a power-control system or SAS. In this regard there would be difficulty with the AK-191B concept. With the engine arrangement used, failure of one lift engine, even at moderate approach speeds, would require the other lift engine to be shut down for pitch balance. There would be insufficient thrust for a go-around with only the cruise engine. Because of the small wing (wing loading of 135 lb/ft^2 (1.01 hg/cm^2)), relatively high-approach speeds (200 knots or greater) are needed for a conventional landing. As noted previously, failure of the SAS would not allow a vertical landing because of poor mechanical control systems characteristics.

Tolerance in conversion (table 14)– The need to ensure against excessive pilot workload, high skill requirements, and excessive pilot attention in carrying out the transition is brought out in both handling-qualities documents. For the VAK-191B, conversion requires relatively complex power management techniques, a large attitude (angle of attack) change as the lift engines are cycled in or out, and close monitoring of angle of attack (to minimize induced drag) because of the poor thrust margin available at the high-speed end of the transition corridor.

Control margins (table 15)– Sufficient control power must be available during transition to allow the pilot to maintain desired attitudes in turbulence and changes in flight-path angle as required for the mission. Specification MIL-F-83300 requires the control margin to be such that 50-percent control margin must remain about any axis at any stage in transition. AGARD Report 577 criteria state that only a margin (beyond trim requirements) for maneuvering is required with the added proviso that simultaneous control input must be considered. Further work must be done to permit a realistic selection of control margins, taking into account the sensitivity to gusts of a given V/STOL concept and the amount of maneuvering required for the mission. In addition, as noted in the AGARD report, a warning should be provided to help guard against reaching unsafe limits in angle of attack or sideslip during transition. In this latter respect, the VAK-191B system was unsatisfactory in that the approach to a loss-of-control situation was masked by the 100-percent authority SAS that tended to create control (maneuvering) deadbands. Pilots did not consider the use of a CRT display in the cockpit, which indicated the amount of control power being used for SAS requirements, to be satisfactory for operational use.

Trim changes (table 15)– The necessity that all trim changes required during transition be small in order to reduce pilot workload and provide for precise flight-path control is noted in both handling-qualities documents. An additional point brought out in AGARD Report 577 which states that trim changes associated with switching from one control mode to another should be satisfactory. In this regard, the VAK-191B was not completely satisfactory. In changing from the attitude mode to the rate-damped mode, the pilot was required to continuously apply nose-down pitch trim in accelerating transition and vice versa during deceleration. During control-mode transfer, a slight PIO tendency existed.

Miscellaneous Characteristics

Control effectiveness during takeoff and landing rollout– The ability to maintain a desired takeoff and landing rollout path under designated wind conditions is a requirement of both handling-qualities references (table 16). This is of particular importance to shipboard operation where only limited space is available. The VAK-191B had generally good nose-wheel steering characteristics for takeoff; however, the "hot" (always engaged) nose-wheel steering was considered undesirable in crosswind landings because of inadvertent pilot inputs. In addition, the crosswind takeoff envelope was too low (10 knots). This was set by lateral-control-power limits required to trim the large, positive dihedral effect and lift-engine gyroscopic moments. In addition, the bicycle gear arrangement made it more difficult to avoid overrotation and damage to the aft fuselage during takeoff. The requirement that a 360° turn be executed within a circle equal to the dimensions of the aircraft could not be met by the VAK-191B.

Power checks before takeoff– The need to check for proper control functioning before reaching takeoff power is self-evident, particularly with full-authority SAS control.. This was not possible with the VAK-191B under all wind conditions because of reingestion tendencies, as previously noted.

CONCLUDING REMARKS

The handling qualities of the VAK-191B VTOL aircraft are compared with current V/STOL handling-qualities requirements. Generally, the aircraft's handling qualities were superior to other V/STOL fighter-type aircraft; however, several deficiencies would seriously affect shipboard V/STOL operation. These include poor hovering precision, inadequate mechanical control characteristics, nonlinear pitch and roll response, an uncommanded movement of the height (thrust) control lever, low-pitch control sensitivity, excessive dihedral effect, and inadequate overall thrust response. The attitude-command control system resulted in reduced pilot workload during hover and low-speed flight.

The study disclosed gaps in the current handling-qualities requirements for operations aboard ships. AGARD Report 577 provides more comprehensive coverage than does MIL-F-83300, particularly in the area dealing with STOL operation.

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Moffett Field, California 94035, March 9, 1979

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TABLE 1.– CONTROL-SYSTEM CHARACTERISTICS: CONTROL BREAKOUT FORCES

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Control breakout forces, lb				
Pitch	0.5– 3	0.5–1.5	2.2	Pitch breakout forces too large for precision hovering – pilot prefers to operate out of breakout range
Roll	0.5– 3	0.5–1.5	2.75	Roll force larger than desired, therefore difficult to determine trim
Yaw	1–10	2–7	11.0	Yaw forces too large, difficult to control sideslip
Height (throttle)	1–3	1–3	Value unknown; preset before flight; not adjustable by pilot	Lack of an adjustable friction device considered a serious deficiency

TABLE 2.– CONTROL-SYSTEM CHARACTERISTICS: CONTROL FORCE GRADIENT AND HARMONY RATIO

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Control force gradients, lb/in.	The force gradient shall not be less than the breakout force			
	Pitch 1–3	0.5–3	2.2	Prefer pitch-force gradient to be reduced for attitude-command control system because of need to hold control force to maintain a given pitch attitude
	Roll 0.5–1.75	0.5–2.5	2.1	Combined effects of high breakout forces and gradient result in poor feel and centering about trim – could contribute to lateral PIO tendencies noted in flight
	Yaw 2.5–10	5–10	13.5	High breakout and force gradient in yaw make accurate control of sideslip difficult when combined with sluggish yaw response in hover and high yaw sensitivity at 60 knots
Control force harmony ratio	Pitch/roll, optimum 2 Yaw/roll, optimum 6	No values stated (response shall be harmonious)	Pitch/roll, 1 Yaw/roll, 6.4	Good harmony important for attitude-command control systems; pitch/roll ratio should be 1 if forces are light, 2 if forces are heavier

TABLE 3.– CONTROL-SYSTEM CHARACTERISTICS: HEIGHT CONTROL AND POWERED-CONTROL SYSTEMS

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Height control systems	Height control should remain fixed unless moved by pilot or some automatic system		Height control (lift engine throttles) can move against the pilot's hand to provide attitude stabilization	Uncommanded movement of height controls caused by the pitch-control system (thrust modulation feedback) was considered unsatisfactory
	Adjustable friction device desirable		No friction adjustment provided	Lack of friction level control unsatisfactory because control can move inadvertently when pilot removes his hand to adjust nozzle vector angle
Powered-control systems	Control-system oscillations should not adversely affect precision of control or cause pilot-induced oscillation	Oscillations of all control systems shall be well damped	Lateral-control system lacks viscous damping	Lateral PIO can occur if stick is released – lack of control-system damping is unsatisfactory
	Failure of powered-control system should not restrict operational maneuvers required for mission		Failure of powered-control system would result in reversion to mechanical linkage system	Mechanical backup system not suitable for hover due to large breakout forces, friction, backlash, and force gradients

TABLE 4.– CONTROL-SYSTEM CHARACTERISTICS: TRIM SYSTEM AND THRUST VECTOR CONTROLS

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Trim systems	Trim operation should be sufficiently rapid to provide low control forces during configuration and speed changes	Trim devices shall operate rapidly enough to provide forces less than 1/3 the limit forces	Two trim rates available (values unknown)	Trim rates not optimized Trim rate too slow for hover operations
	Provision shall be made to prevent "runaway" trim	Failure to level 2 and 3 requirements include trim sticking and "runaway"	No provision to prevent trim "runaway"	Inability to prevent trim "runaway" was considered unsatisfactory
	Failure of powered-control system or SAS should not affect ability to trim		Failure of SAS can prevent trimming	No comments
Thrust vector controls	Variable-thrust vectoring rate is desirable; selected setting must be maintained indefinitely; should be able to adjust thrust-vector control without compromising ability to manage other controls		Variable rate (deg/sec) of thrust vector nozzles available by proportional thrust-vector lever movement	Variable-rate vector control was satisfactory; nozzles tended to drift from selected position – undesirable

TABLE 5.– LONGITUDINAL STABILITY AND CONTROL: PITCH-CONTROL POWER; PITCH-CONTROL SENSITIVITY; AND LINEARITY

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Pitch-control power	0.4–0.8 rad/sec^2	±3.0° attitude change after 1 sec (wind from most critical direction)	1.0 rad/sec^2; 8.0° after 1 sec; ±15° pitch attitude available	Total control power is adequate but response was lower than desired in the thrust-modulation deadband; need 20° nose-up and 15° nose-down attitude
Pitch-control sensitivity	3°–5°/in.	3°–20°/in.	3.5°/in.	Pitch response is sluggish for small inputs
Linearity (a/c response to control input	Constant; if not constant, no abrupt increase or change in sign	There shall be no objectionable nonlinearities	Nonlinear in going from bleed air to thrust modulation; A/C oscillations of 0.5 Hz for small control inputs	Small pitch-control inputs within the differential thrust deadband resulted in oscillatory aircraft motion

TABLE 6.– LONGITUDINAL STABILITY AND CONTROL: LONGITUDINAL CONTROL CHARACTERISTICS IN TAKEOFF

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Longitudinal control characteristics in takeoff	Control effectiveness should not restrict STOL operation; shall be sufficient to initiate rotation at the designated speed or at least 2.0 sec before liftoff; adequate control margin and pitch rate damping shall exist to prevent rotation to undesirable attitudes; control shall be sufficient to rotate in ground effect	Elevator control shall not restrict takeoff performance and shall be sufficient to prevent overrotation to undesirable attitudes.	Pitch rotation obtained by lift-engine thrust modulation	Due to landing gear geometry, liftoff by rotation was accompanied by pitch overshoot requiring corrective pilot action Due to control and stability augmentation system functions, feedback into the lift-engine throttle and reduction in lift-engine thrust occurred; this feature is highly undesirable because LE throttle is unguarded
		Satisfactory takeoffs shall not depend on complicated control manipulation; control travel during takeoff shall not exceed 75 percent of total travel	Approximately 15 distinct steps required in STO procedure; lift engines are started during takeoff run to minimize ground erosion and hot-gas ingestion	Due to high workload associated with lift-engine start during takeoff roll, the PR is 7; if wheel brakes are released after LE are running and checked out, PR is 2

TABLE 6.– CONCLUDED

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Longitudinal control characteristics in takeoff (continued)	For all types of takeoff operation, desirable to check for proper control functioning during run-up at less than takeoff thrust			Need to functionally check lift-engine performance for proper pitch-control functioning during engine run-up urgently exists

TABLE 7.– LONGITUDINAL STABILITY AND CONTROL: LONGITUDINAL CONTROL CHARACTERISTICS IN LANDING

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Longitudinal control characteristics in landing	Pitch control in conjunction with other controls, should be capable of flaring aircraft and achieving desired landing attitude from both steep and shallow approach angles	Elevator cockpit control shall be sufficiently effective that the geometry-limited touchdown attitude can be obtained in proximity to ground	Attitude-control system and ME nozzle vectoring allowed setting of pitch attitude and approach speed; a limit of 4.8° γ existed at 60 knots Va due to landing gear strength; a reduction in sink rate occurred when entering ground effect, requiring a further power reduction to achieve touchdown at the desired spot	Pitch control satisfactory for short landings; ground-cushion effect noticeable, particularly on shallow approaches; cushioning effect enhances flight safety on steep approaches due to low landing gear strength, but adversely affects precision of touchdown. If a 5°–6° attitude is commanded at touchdown, SAS control laws are such that LE throttle lever can be snatched from pilot's hand

TABLE 8.– LATERAL-DIRECTIONAL STABILITY AND CONTROL: ROLL-CONTROL POWER, SENSITIVITY, AND LINEARITY

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Roll-control power	0.4–1.5 rad/sec^2	±4.0° attitude change after 1 sec	1.4 rad/sec^2; 13.4° after 1 sec; for full δ_a ±15° roll attitude available SAS on	Adequate for hover with no wind; inadequate for full flight envelope maneuvering; need more than ±15° roll angle for STOL maneuvering
Roll-control sensitivity	3–5°/in.	4–20°/in.	5.4°/in.	Lateral response too sensitive in hover tending toward PIO
Linearity	Constant; if not constant no abrupt increase or change in sign	There shall be no objectionable nonlinearities in aircraft response	Abrupt change in roll response when lateral control was returned to neutral in sidestep maneuvers	Roll overshoot on recovery from sidestep maneuvers was objectionable and could lead to PIO
			SAS can exert 100-percent control authority	Loss of lateral control masked from pilot by capability of 100-percent authority SAS to create control deadbands near full-stick deflection

TABLE 9.– LATERAL-DIRECTIONAL STABILITY AND CONTROL: CROSS-COUPLING AND DIHEDRAL EFFECT

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Cross-coupling	At reference speed for STOL operation, $\Delta\beta/\Delta\phi$ not to exceed 0.3 to 0.5 or 20° sideslip angle	$\Delta\beta/\phi$, maximum change in sideslip angle to initial peak bank angle not to exceed 1.65	$\Delta\beta/\Delta\phi$ is essentially zero in transition speed range	Satisfactory, little sideslip induced in aileron-only turns in speed range up to 120 knots
Dihedral effect	Positive dihedral limited so that sufficient roll control remains to correct for gusts, upsets, and maneuvering	Positive dihedral effect should never be so great that more than 50-percent roll-control power needed for sideslip excursions	At 100 knots and $\alpha = 5°$, β limited to 5°, at 50 knots, $\alpha = 10°$, β limited to 10°	Operational crosswind envelope of 10 knots unsatisfactory; no warning of sideslip limits, unacceptable for operational use

TABLE 10.– LATERAL-DIRECTIONAL STABILITY AND CONTROL: YAW-CONTROL POWER, SENSITIVITY, AND CROSS COUPLING

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Yaw-control power	0.35–0.8 rad/sec^2	±6.0° attitude change after 1 sec	0.4 rad/sec^2 (30°/sec yaw rate) 12° after 1 sec full rudder input	Yaw considered too sluggish in hover
Yaw-control sensitivity	0.08–0.2 rad/sec^2/in.	6.0–23.0° heading change after 1 sec/in. δ_r	0.085 rad/sec^2/in. 4° in 1 sec/in. δ_r	Yaw-control sensitivity was low in hover but heading-control accuracy was adequate
			Yaw-rate command system gain constant over transition speed range to 120 knots	Constant yaw rate per inch of rudder pedal deflection regardless of forward speed made turns difficult and resulting sideslip excursion reduced lateral-control availability for maneuvering
Cross coupling	Rolling moment variation with yaw rate shall be positive but not require more than 50-percent roll control to trim for $\delta_{r_{max}}$		Large lateral velocity developed during full rudder pedal input turns	Preferred not to use rudder for turn entries because of large rolling moment due to sideslip

TABLE 11.– VERTICAL FLIGHT CHARACTERISTICS: GROUND EFFECT

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Ground effect	Downwash/ground interference should not result in unsatisfactory characteristics during hover and STOL operations		Positive ground effect evident in no wind, stationary hover; maneuvering or tailwind conditions could result in recirculation in rear lift engine	Height control difficult due to nonlinear response associated with positive ground effect, recirculation (exhaust ingestion) in rear lift engine resulting in pitch attitude changes, and consequent reduction in height control power
	Following failure of a power control system or SAS, safe landing should be possible		Reversion to manual-control system increases control-system friction to large values	Loss of either powered control or SAS would make safe landing questionable

TABLE 12.– VERTICAL FLIGHT CHARACTERISTICS: HOVERING PRECISION

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Hovering precision	It should be possible to takeoff, hover continuously IGE, and land, all within an area 1.1 X span and length of aircraft	No requirement	Precision VTO (no wind) requires a slight nose-up attitude adjustment after liftoff to stop forward drift; due to engine placement used on this VTOL concept, recirculation can occur with possible engine surge and reduction in T/W	Precision of height control varied with T/W more than expected; at low T/W (1.05), vertical response is nonlinear and controllability is questionable if combined with rapid pitching maneuvers due to LE throttling; precision VTO characteristics considered inadequate for shipboard operations at T/W < 1.1; not possible to meet spotting accuracy factor of 1.1
	It should be possible to hover continuously OGE within an area 1.2 X span and length of aircraft			Spotting accuracy was improved OGE; attitude stabilization system characteristics were satisfactory

TABLE 13.– VERTICAL FLIGHT CHARACTERISTICS: VERTICAL THRUST MARGIN AND THRUST RESPONSE

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Vertical thrust margins	Maximum T/W available at the most critical value of vertical velocity damping shall be: Takeoff: 1.05 and not less than 600 ft/min climb rate Landing: 1.03–1.10	Steady-state T/W available, shall not be less than 1.05	Height control obtained by combined thrust of lift and cruise engines; T/W available can go from 1.1 down to 1.0 in ground effect	Height control with matched throttle (lift/main engines) was satisfactory when T/W = 1.1; but inadequate when reduced to 1.05; height control with split throttle resulted in speed/altitude coupling due to reduced throttle sensitivity, exhaust geometry, and asymmetric lift-engine response resulting in unacceptable height control
Height control sensitivity and thrust response	Normal acceleration, (g/in.) should be in the range 0.1 to 0.4		Split-throttle operation resulted in a sensitivity of 0.04 g/in.	Low sensitivity resulted in excessive height-control lags; desire approximately 0.075 g/in. per throttle
			Front lift engine has faster thrust response	This caused problems in liftoff dynamics, linearity of longitudinal control, and height control.
	First-order time constant should not be greater than 0.5 sec	Achieve 63 percent of commanded incremental thrust in not more than 0.3 sec	Time constant of combined throttle response varied between 0.4 and 0.7 sec	Lift-engine thrust response considered good – cruise engine response was inadequate and led to overcontrol tendencies

TABLE 13.– CONCLUDED

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Height control sensitivity and thrust response (continued)	No requirement	No requirement	Automatic limiting of maximum power is incorporated resulting in a region on throttle deadband	Pilot should be warned of approaching deadband operation and a thrust margin of about 10 percent should be provided Deadband resulted in excessive degradation of height control due to nonlinearity and reduced sensitivity

TABLE 14.– TRANSITION CHARACTERISTICS: ACCELERATION/DECELERATION FLEXIBILITY OF OPERATION AND TOLERANCE IN CONVERSION

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Acceleration/ deceleration	Acceleration and deceleration values up to 0.5 g in level flight are desired It should be possible to accelerate continuously from a rolling takeoff to V_{con} and vice versa	It should be possible to accelerate rapidly and safely to V_{con} and decelerate rapidly and safely; time taken for these maneuvers to be designated by mission requirements	Maximum deceleration limited to 0.25 g Acceleration capability reduced from a maximum of 0.5 g at takeoff to 0 g at 200 knots Trim pitch force change unknown	Need no more than 0.15 to 0.18 g capability deceleration for night or IFR operation Acceleration inadequate in upper transition speed range; transition mode required constant pitch trim to prevent pitch-up during acceleration Trim requirements should be minimized in transition due to high pilot workload
Flexibility of operation	Direction of transition should be easily reversible Failure of a single-engine, SAS, or power-control system shall still allow a safe landing on wave-off	It should be possible to stop and reverse the transition quickly and safely	Transition performed by positioning cruise engine nozzle A lift-engine failure would require a conventional landing	Transition could be stopped or reversed at any time Conventional landing would be extremely dangerous because of poor flight-path control and field length requirements
Tolerance in conversion	Changing from hover to conventional flight and vice versa with low pilot workload	It should be possible to change from hover to V_{con} and vice versa without excessive pilot skill and attention	Conversion requires complex lift-engine operation, large attitude change, and close airspeed control	Conversion sequence too complex and pilot workload too high for operational use

TABLE 15.– TRANSITION CHARACTERISTICS: CONTROL MARGINS, TRIM CHANGE

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Control margins	Margin of control power about any axis should not be less than that specified for maneuvering	Margin of control power remaining at any stage in transition should not be less than 50 percent of total available about any axis	Margins in control remaining displayed on CRT	
	True value of control margin available should be apparent to pilot		Control positions do not indicate margins of control power available	Approach to loss of control was masked from pilot by capability of 100-percent-authority SAS to create deadbands near full-control stick throw
Trim change	Trim changes on control-mode switch-over shall be small, gradual, and compatible with trim rate available	Trim change should be small and gradual and longitudinal control force not exceed 15 lb pull and 7 lb push	Trim changes unknown	Transition mode required constant pitch trimming to prevent pitch-up during acceleration and vice versa; trim requirements during transition should be minimized to reduce pilot workload.
				During control mode transfer a slight PIO tendency existed

TABLE 16.– MISCELLANEOUS CHARACTERISTICS

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Control effectiveness during takeoff, landing rollout	Maintain desired path and attitude by normal use of cockpit controls and steering controls in designated crosswinds	Aileron, elevator, and rudder cockpit control and other normal means of control shall be adequate to maintain a straight path on the ground or other landing surface in crosswinds up to 35 knots	Bicycle gear with outriggers	Excellent nose-wheel steering on takeoff, but "hot" (always engaged) nose-wheel steering limited crosswind operation on landing (see text) Bicycle landing gear arrangement can result in overrotation tendency and damage to aft fuselage after takeoff
			Nose wheel steering by rudder pedals with two ranges of sensitivity – low range for takeoff and high range ±40° for taxi	Directional control during takeoff was good Aft position of main gear results in increased nose-wheel lift/holdoff speeds for STOL operations which reduces wing lift effectiveness
	It should be possible to make a 360° turn within a circle equal to major dimension of aircraft in designated wind conditions	It should be possible to make 360° taxiing turns within a circle whose radius equals major dimension of aircraft in winds up to 35 knots	Limited nose wheel steering range restricted to ±40°	Outrigger landing gear design enhances deck motion and gust capability; however, combined gear geometry and non-wheel steering characteristics would result in excessive turning radius for LPH operation

TABLE 16.– CONCLUDED

Item	AGARD report R-577 (ref. 1)	MIL-F-83300 (ref. 2)	VAK-191B	Pilot comments about VAK-191B
Power checks prior to takeoff	For VTO, STO, and RTO, it should be possible to check for proper control functioning before reaching takeoff power		Lift engine run-up to functionally check out engines was not possible under static conditions	It is necessary to check out functioning of fuel control, flight controls. and engine power before takeoff

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15. Supplementary Notes		

16. Abstract

The handling qualities of the VAK-191B VTOL aircraft are compared with current V/STOL handling-qualities requirements. Generally, the aircraft's handling qualities were superior to other V/STOL fighter-type aircraft; however, several deficiencies would seriously affect shipboard V/STOL operation. These include poor hovering precision, inadequate mechanical control characteristics, nonlinear pitch and roll response, an uncommanded movement of the height (thrust) control lever, low-pitch control sensitivity, excessive dihedral effect, and inadequate overall thrust response. The attitude-command control system resulted in reduced pilot workload during hover and low-speed flight.

The study disclosed gaps in the current handling-qualities requirements, particularly for operation aboard ships. AGARD Report 577 provides more comprehensive coverage than does MIL-F-83300 in the area dealing with STOL operation.

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